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Seasonal effects on the stiffness properties of a ballasted railway bridge

Ignacio Gonzales, Mahir Ülker-Kaustell *, Raid Karoumi

KTH Royal Institute of Technology, Brinellvägen 23, SE-100 44 Stockholm, Sweden

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ABSTRACT

In this article it is shown empirically that ballasted bridges in cold climates can exhibit a step-like variation of their natural frequencies as the yearly season changes. The bridge under study was observed to have significantly higher natural frequencies (as much as 35%) during the winter months compared to the summer. This variation was rather discrete in nature and not proportional to temperature. Furthermore the increase in natural frequencies took place only after the temperatures had dropped below 0 °C for a number of days. It was thus hypothesized that this change in natural frequencies was due to changes in the stiffness parameters of some materials with the onset of frost. In low temperature conditions not only the mean value of the measured frequencies increased, but also their variance increased considerably. Given the large spread of the measured natural frequencies, the stiffness parameters were assumed to be stochastic variables with an unknown multivariate distribution, rather than fixed values. A Bayesian updating scheme was implemented to determine this distribution from measurements. Data gathered during one annum of monitoring was used in conjunction with a finite element model and a meta model, resulting in an estimation of the relevant stiffness parameters for both the cold and the warm condition.

1. Introduction

The influence of long periods of low temperature on the dynamic properties of ballasted railway bridges has not been given much attention. This paper presents a study of the influence of seasonal effects on the natural frequencies of a ballasted single span steel-concrete railway bridge. It is shown that the natural frequencies of the first vertical bending and torsional modes of vibration increase markedly during the cold period of the year. An analysis of measured free vibration signals during one annum is used as a basis for a Bayesian updating procedure, which is applied on a three dimensional finite element model of the structure.

In dynamic assessments of existing railway bridges with the purpose of increasing the allowable train speed and/or axle loads, the analyst primarily needs information regarding the natural frequencies and the corresponding modal damping ratios of the first few modes of vibration. This information can be obtained by fairly simple instrumentations using the free vibrations from passing trains. However, as will be shown, the natural frequencies estimated during the cold season can be misleading. The natural frequencies are needed to estimate the critical train speeds at which train-bridge resonance may occur [1–3] and can be used in various model updating schemes, see for example [4,5], preferably together with their corresponding mode shapes. The damping ratios are needed to estimate the response amplitudes for different train speeds and will not be treated here. Naturally, estimates of the properties of higher order modes would also be desirable, but are more difficult to obtain.

In applications of structural health monitoring (SHM), an awareness of temporal variations in the dynamic properties of the structure being monitored is also very important. Such systems need to update the "healthy" state according to the seasonal variations so as to avoid false positives as suggested by Peeters et al. [6].

Resonance between the train and the bridge can occur whenever the train passing frequency (i.e. the ratio between the train speed v and some characteristic length L such as the bogie distance or the carriage length) coincides with a natural frequency f_n of the bridge. Clearly, the modes of vibration with the lowest frequencies will be more sensitive to this phenomenon because they will be excited by lower train speeds, but also because they are not as efficiently attenuated as higher order modes. Therefore, accurate estimates of the natural frequencies are very important and overestimated frequencies may lead to unsafe decisions as the critical train speeds are then also overestimated. It is a well-known fact that for linearly elastic, lightly damped structures, the natural frequencies and their corresponding mode shapes essentially depend on the spatial distribution of stiffness and inertia. The inertial properties of the structure can typically be fairly well estimated using the design drawings, although some variability in the amount of ballast and in the density of the ballast is expected due to track maintenance operations.

* Corresponding author. Tel.: +46 8 7907949.
E-mail address: mahir.ulker@byv.kth.se (M. Ülker-Kaustell).

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The goal of this study is to infer some stiffness properties of the ballast and subsoil from measurements carried out on the bridge, taking seasonal effects in consideration. However, as will be shown, other mechanisms may be relevant in describing the theoretical modes of vibration of the structure in a sufficiently accurate way. Bayesian updating of a 3D finite element (FE) model with Markov-Chain Monte Carlo (MCMC) sampling is applied to determine posterior distributions of the uncertain parameters in the warm and cold states of the bridge. The process used to obtain the distributions of the chosen uncertain parameters/mechanisms can be divided in the following steps:

1. Data collected for over one year of monitoring was analyzed. The eigenfrequencies for the first vertical bending mode and the first torsional mode were extracted from the data and studied.
2. A FE model of the structure was devised. The model was parameterized so that the parameters representing the uncertain parameters/mechanisms could be treated as unknown variables. The FE model thus represents a function that takes the uncertain stiffness parameters as arguments and returns the eigenfrequencies corresponding to the studied modes of vibration.
3. A large number of inputs (uncertain parameter sets) were evaluated in the model and the sought eigenfrequencies obtained by solving the corresponding eigenvalue problem. The parameter ranges were chosen to cover all the values that can be expected within reasonable limits. From this result a meta model was constructed by fitting a Gaussian Process. The purpose of the meta model was to bypass the computationally expensive model in the following step.
4. A Bayesian updating scheme was used to update the distribution of the chosen stiffness properties, using the meta model to calculate the likelihood of any given input.

The result of this process (graphically depicted in Fig. 1) is an estimation of the distributions of the uncertain parameters, which result in a frequency distribution in the theoretical model that matches the observed one. In Section 3, we describe the structure, its instrumentation and an analysis of the estimated natural frequencies. The Bayesian updating scheme is described in detail in Section 4 and the finite element model used to define our theoretical model is described in Section 5. The results of the model updating are presented in Section 6 and its implications are discussed in Section 7, which also presents a summary of the conclusions drawn from the study and suggestions for future research.

2. Background

Studies of this kind are not very common in the literature. However, some references do treat the issue and related questions.

Xia et al. [10] presented a review of temperature effects in the context of vibrations of civil structures, but the temperature span mainly covered temperatures above the freezing point. In reference [6], the variation in the first two natural frequencies of a road bridge during temperature variations down to approximately −5 °C was reported. A clear, discontinuous increase of approximately 10% was found around 0 °C. Yang et al. [12] reported variations in the natural frequencies of the first transversal modes of vibration of a road bridge of several spans due to seasonal variations. The frost in the ground was found to be a likely cause. Similarly, Alampalli [13] observed large variations in the first three modes of vibration in a steel-concrete composite road bridge during a 9 month period and suggested that the freezing of the supports could give a reasonable explanation to these observations. Zabel et al. [11] reported a 30% increase in the natural frequencies of the first 6 modes of vibration of a short span railway bridge when the temperature decreased below 0 °C.

Simonsen et al. [8] presented results of laboratory tests on the resilient modulus of soil materials ranging from marine clay to gravelly coarse sand. The resilient modulus was found to increase by 1–2 orders as the temperature was decreased from 0 °C to −10 °C and the most considerable increase appeared in the temperature interval (−5, 0) °C. The resilient modulus in the unfrozen state, after one freeze-thaw cycle, was found to decrease by approximately 20% for the gravelly sand and as much as 60% for

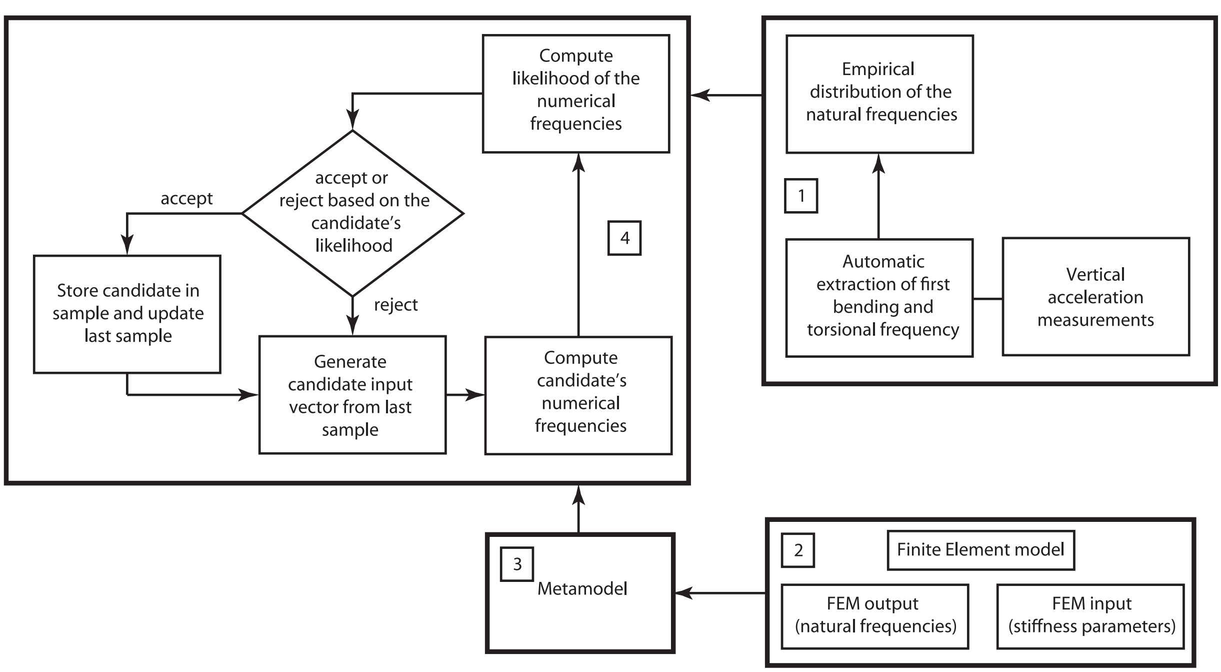

Fig. 1. Schematic diagram of the updating method used in this study. It includes the acquisition and analysis of data (upper-right section), the development of the model and meta model (lower-right corner) and the updating procedure (left section) that builds on the results of the two previous steps.